# Optical Fiber Sensors
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**Lecture: 8**
## Optical Receivers – 3

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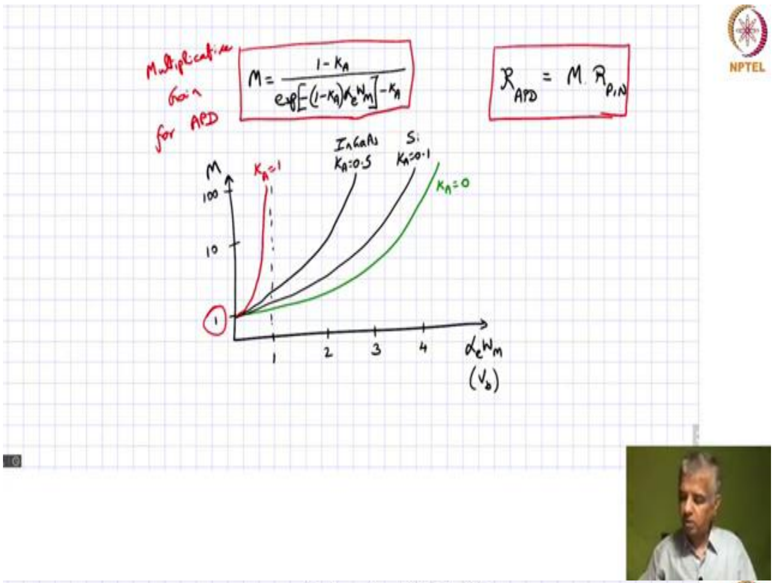
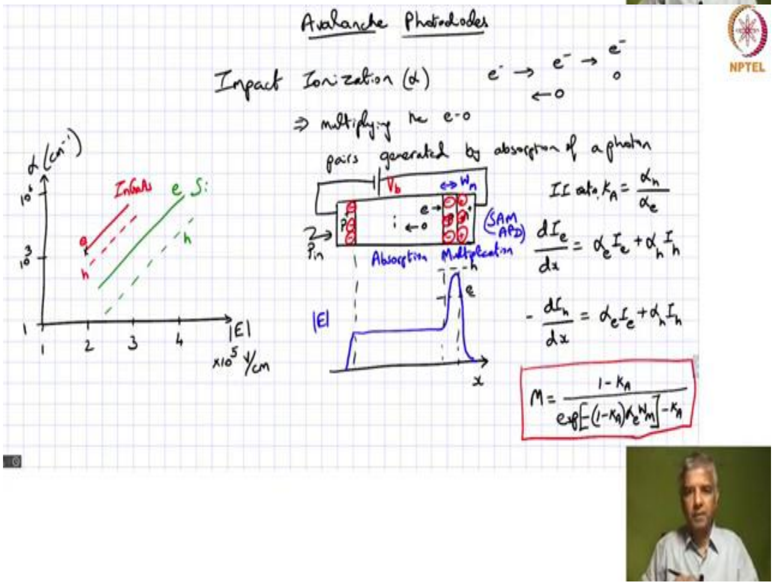

Multiplication Gain for APD

$$M = \frac{1-k_A}{\exp[-(1-k_A)\alpha_e W_m] - k_A}$$

$$\mathcal{R}_{APD} = M \cdot \mathcal{R}_{P,I,N}$$


Avalanche Photodiodes

Impact Ionization ($\alpha$)

⇒ multiplying the e-o pairs generated by absorption of a photon

II rate, $k_A = \frac{\alpha_h}{\alpha_e}$

$$\frac{dI_e}{dx} = \alpha_e I_e + \alpha_h I_h$$

$$-\frac{dI_h}{dx} = \alpha_e I_e + \alpha_h I_h$$

$$M = \frac{1-k_A}{\exp[-(1-k_A)\alpha_e W_m] - k_A}$$

Hello, so we have been talking about the design of optical receivers from the perspective of building optical sensors. And so far, we started looking at the front end of the optical receiver, which is the photodiode and we looked at the properties of PI and photodiode and during the last lecture, we started talking about Avalanche Photodiodes, we looked at how Avalanche Photodiode works, it is based on this impact ionization process. And then we came to the point where we were defining the multiplicative gain as a function of the bias voltage that we provide to the Avalanche Photodiodes.

And one thing that we realized was that it is best that the K A value which corresponds to the impact ionization ratio, the impact ionization coefficient for holes divided by the impact ionization coefficient for electrons. If that K A value, if it is away from 1. Then we make sure, then it means that one of the (())(1:35) pieces, whether the electrons or the holes are participating or generating that impact ionization and that actually provides much better gain without incurring a lot of noise.

So, we talked about noise, very briefly, our we just mentioned about noise, we do want to go a little more into detail as to, what are the kind of noise sources in the receiver. But before we go to that, we will just complete our discussion with respect to Avalanche Photodiodes. So, essentially, what we are saying is, when you are looking at the responsibility of APD. That corresponds to M times the responsibility for the PIN structure. So, that is a key thing to keep in mind about avalanche photodiodes. So, effectively, if you say, VB is 0, then your gain value is 1.

So, if you take an APD and you do not actually provide an external bias, then it essentially works like a pin. But beyond that, you can actually get some multiplicative gain and through that, you can improve the responsivity of the photodiode which corresponds to the amount of photocurrent that you generate for a certain amount of optical power that is incident on the photodiode.

Now, that is hopefully, that is clear. Now, let us actually move on and try to understand what we mean by, or try to quantify what we mean by, having more noise as you go to higher gain value. So, how do you quantify that? Well, that can be quantified by what is called the excess noise factor.

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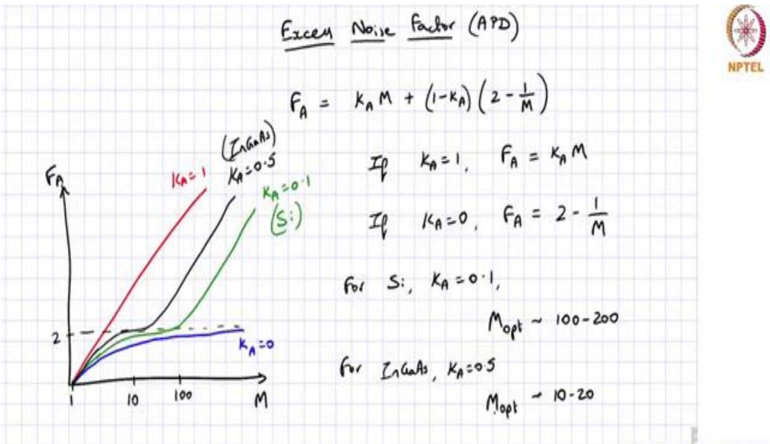

Excess Noise Factor (APD)

$$F_A = k_A M + (1-k_A)\left(2-\frac{1}{M}\right)$$

If $k_A = 1$, $F_A = k_A M$

If $k_A = 0$, $F_A = 2 - \frac{1}{M}$

For Si, $k_A = 0.1$,

$M_{opt} \sim 100-200$

For InGaAs, $k_A = 0.5$

$M_{opt} \sim 10-20$

We can go to a fresh page and look at that. So, what we are talking about is, maybe I can just go back to my black color, excess noise factor as far as APD are concerned. So, the excess noise factor is quantified as this term F A. There is actually an empirical relationship for that connecting this excess noise factor to the avalanche gain, that multiplicative gain is given by M. So, it is K A multiplied by M plus 1 minus K A, multiplied by 2 minus 1 over M. So, that is actually an empirical relationship that we have for the excess noise factor.

So, now, let us look at how this works. So, let us actually plot a graph of F A, the excess noise factor as a function of M. And let us actually look at the role of K A in terms of the excess noise factor. Now, to look at that, first of all, we can substitute different values of K A and see how this expression works out.

So, the easiest thing is if K A equals to 1. So, what happens? Well, if K A equals to 1, then the second term disappears, and you are just left with that first term. So, this is basically F A is K A multiplied by M. By the way, if you are wondering where all this is coming from, these are all stuff that we taught in introduction to photonics.

But if you just want to go back and look at that text, there are several excellent texts that talk about PIN and APD photodiode, as well as the laser sources and that we talked about previously. Sally and (())(06:18) is one very good reference. But most of the notations that I am following is actually from this book by G.P. Agrawal, which is on Fiber Optic Communication System. So, if you want to go back and look at that, you can follow that book.

So, let us look at the case of K A equals to 1, if we were to draw that that just basically a linear relationship. So, with the slope of 1, so just a straight line. So, what does that tell you? Well, that tells you that whatever gain you are having from your APD, you have a corresponding noise that is coming into the picture as well.

So, when you look at the signal to noise ratio, you may not be gaining much as far as this K A equal to 1 value is concerned. Now, let us actually look at the other extreme, what if K A equal to 0? Well, if K A equal to 0, F A becomes I mean, the first term essentially vanishes, and the second term K A is 1. So, F A is 2 minus 1 over M.

So, how do we actually represent that, let us say F A equal to 2, that corresponds to this line here. So, 2 minus 1 over M is a function that is going to be asymptotic with respect to 2, so it is going to be something like this. So, what does that tell us? Well, it says that whatever could be the value of M, you are going to cap your noise, that is the competition between the noise due to the competition between two carriers, two different types of carriers, initiating the avalanche process.

So, that noises caped at a value of 2. So, you can keep increasing the gain and you will not incur any extra noise than this factor of 2. So, that means that you can get whatever signal to noise ratio you want. Well, that is a hypothetical case, because there is no material with K A equal to 0.

So, for example, if we consider silicon, silicon has got a K A of 0.1. So, let us actually look at how K A of 0.1 would look like. Well, that would be closer to 1 for low values of M. But as you go to higher values of M, it is going to start being parallel to this other line, the other line is K A equal to 1 and here we are talking about equal to 0.1, which is the K A is for silicon.

And just make sure this label is also there. So, this is K A equal to 0. So, what it says is that it behaves like an ideal, K A equal to 0 type of thing for low values of M, so that is very good. But beyond a certain point, as you increase M, you are starting to also scale up in F A.

Essentially this term, the first term starts dominating beyond a certain value of M and for lower values of M, this term is dominating for higher values of M, this term is dominating. And when you go to this regime, where this term is dominating, then you lose all the benefits of using your APD.

So, that is to tell that, if you want to use an APD, you probably want to use it up to this point, this value of M beyond which, there is really no point. So, just to complete the picture, let us look actually look at K A equals to 0.5. And that again is going to look similar to this case of K A equal to 0.1 at low values.

But then, as you increase further, it is going to start behaving like K A equal to 1, case at higher values of M. So, here the optimum value may be something around here, which is in the order of 10, and whereas, here this is in the order of 100. So, you can say, let us actually write it out.

So, if you talk about silicon, for silicon K A equals to 0.1 and what we find is this the gain, the multiplicative gain, until which you can improve your signal to noise ratio or the multiplicative gain beyond which the signal to noise ratio is not improving or it is only going to start degrading is what you call as the optimum gain. So, this for K A equals to 0.1 the optimum gain value could be in the order of 100 to 200.

In contrast for indium gallium arsenide, K A equals to 0.5, we are tracking this curve over here and what that tells you is that the M opt is going to be more in the order of 10 to 20. So, you clearly with indium gallium arsenide, you would clearly have, you are not going to be able to use an APD with much higher values than these. There are some specific conditions under which you could possibly push this slightly like cooling the diode and all that. I will tell you a little later as to why that makes sense.

But you could possibly improve the optimum value for indium gallium arsenide to maybe 30 or 40 by cooling the diode. We will come back to that later. So, that is actually the some of the properties of this avalanche photodiode.

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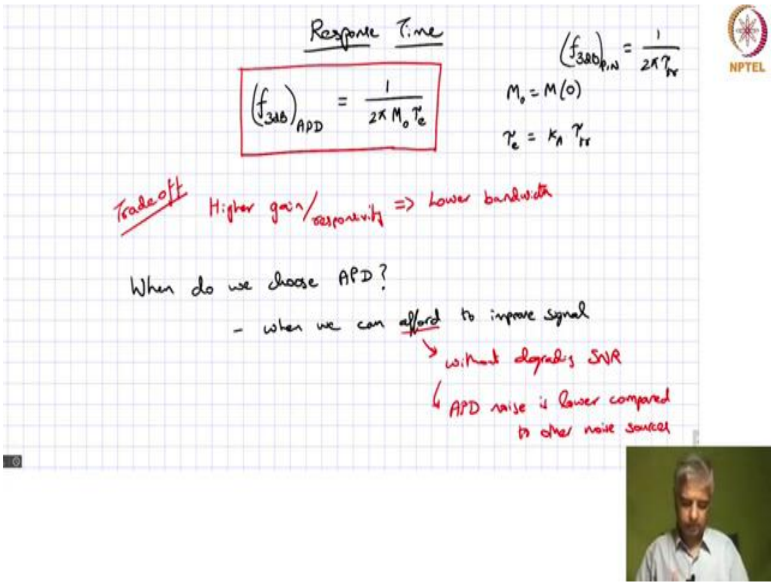


Response Time

$$(f_{3dB})_{PIN} = \frac{1}{2\pi\tau_{tr}}$$

$$\boxed{(f_{3dB})_{APD} = \frac{1}{2\pi M_0 \tau_e}}$$

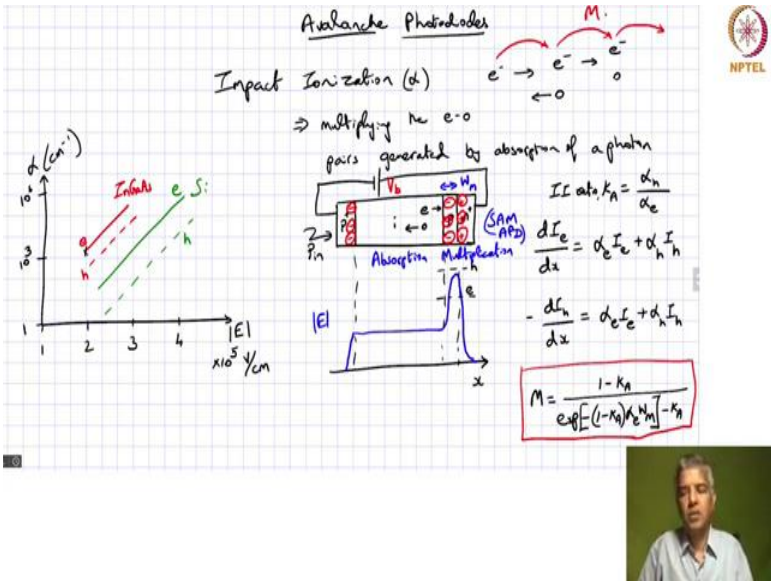
$M_0 = M(0)$

$\tau_e = k_A \tau_{tr}$

Tradeoff Higher gain/responsivity => Lower bandwidth

When do we choose APD?

- when we can afford to improve signal
  - without degrading SNR
  - APD noise is lower compared to other noise sources



Now, let us look at another aspect of this which is basically the response time of avalanche photodiodes. In a PIN photodiode, we said the response time is limited by the transit time of the carriers within this PIN structure. So, we said F3DB, in that case, is equal to, let us just write down F3DB for a PIN. We said it could be 1 over 2 pi tau T R, where tau T R corresponds to the transit time of the carriers. Now, if we do the same thing for an APD. What do you think is going to be the limiting factor?

Well, of course, there is that transit time involved here, but there is going to be some additional factor that determines the response time, which is, if we go back and look at this picture over here, this is actually a sequential picture by which we are getting gain from here to here, and then and then after this has happened, then this happens.

And then from here, you might have, even more, electron-hole pairs generator. So, that is the multiplicative gain process that we are talking about. So that multiplicative gain is going to take time. So, it is going to take a finite amount of time to go through that cascade to go through that avalanche.

So, effectively, when you look at the F3DB of an APD, I am not deriving this in the interest of time, but you can go back and look at the text that I mentioned, you will find this dealt with a little more detail, but it corresponds to 1 over 2 pi multiplied by this value of M and I would actually denote it as M naught. So, what do I mean by M naught? M naught is basically the gain at zero frequency at D C.

So, that actually is what we are denoting here, that is the multiplicative gain, multiplied by some time constant, and that time constraint you can call it as tau E is the effective time constant. And turns out this effective time constant is actually given by or it can be approximated as K A multiplied by tau T R.

So, K A, like we said it can be a value of 0.5 for indium gallium arsenide and 0.1 for silicon. And correspondingly, when you look at the gain value also, the gain value could be in the order of 10 for indium gallium arsenide, it could be in the order of 100 for silicon, but this is the trade of now, what we are talking about here, because of this what we are saying is higher gain or you can just say that corresponds to higher responsibility, that implies you have lower bandwidth, slower response time you can call that. So, higher gain corresponds to lower bandwidth, or in other words, if you want to achieve higher bandwidth, you will have to do that, at the expense of dealing with lower gain value.

So, essentially how do you control the gain value? Well, in APD, we saw that we control it using your bias voltage. So, if you want to have high gain, you increase your bias voltage up to the, so, that the gain value goes to close to the optimum gain value. On the other hand, and that point the bandwidth is lower.

But if you want to actually have better bandwidth, you scale down your voltage so that you can work with lower gain value. So, that is actually a classic trade-off that you have as far as avalanche photodiodes are concerned. So, that is something that is very important to keep in mind.

Now, the other question could be, when do we choose an APD? As supposed to choosing a PIN because PIN, we know the simplest structure, it is got all these properties that is very well defined. They may not be as much noise, that the excess noise factor that we saw that does not come into the picture as far as PIN is concerned. So, that may be better for certain application.

So, then the question is, when do we choose APD? We choose APD when we can afford to improve the signal. And what do we mean by this word afford? So, what we are talking about is without degrading the signal to noise ratio. Now, of course, we have not talked about noise very much. So, that is something that, we will go into little more detail shortly.

But before we talk about this, what do we mean by this? Essentially, that without degrading signal to noise ratio means that the APD noise, the excess noise provided by the APD is lower compared to other noise sources. So, if you have the noise due to APD being lower compared to other noise sources, that is when you actually, that is when you can afford to boost up the signal and that is when you want to use an APD.

So, we will look at some specific conditions related to this, but to understand this point a little more, we need to understand noise in the receiver, and to understand noise in the receiver, you need to now understand how you are basically is starting with a photodiode, starting with some optical power and how are we converting that to a voltage. So, we need to understand the receiver construction beyond the photodiode. So, that is what we will look at next.